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Toward the Optimization of Control of Unsteady Separation

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Abstract:

Regardless of our understanding, or the lack of it, of the complicated physical process, means can always be found to alter the occurrence and development of unsteady separation. To be able to optimize the control of separation, however, requires the identification of the critical aspects to which the intervention may be focused and achieve the desired result with minimum waste of effort. The Lagrangian analysis of unsteady boundary-layer traces the trajectories of individual fluid particles, and reveals the 'bad seeds' that, through extreme deformation in the direction normal to the wall, eventually develop into a virtual barrier and cause the ejection of boundary-layer material into the main stream. It follows logically that separation can be triggered or delayed most effectively by targeting these 'bad seeds'. Since they are normally interior points of the boundary layer, attempts to influence them through the boundary conditions are necessarily indirect. Furthermore, as the strategy has to be the modification of the growing process of the 'bad seeds', whatever may be the intervention scheme, it needs to be strong enough and early enough. In Shen and Wu (1988), examples of how acceleration/deceleration of the (2D) body, as well as the moving wall (of a rotating cylinder), may affect the development of the bad seed toward separation are shown. In fact it was mentioned therein that the results might be the first step for a feasibility study of the control of unsteady separation.

A practical difficulty of making Lagrangian calculations of the boundary layers, even in the simpler 2D case, is the loss of accuracy due to the continuing distortion of the fluid element with time. This is accentuated in airfoil-like slender bodies (Wu, 1985). More problems arise if wall suction or blowing is added. These however cause much less trouble for the more conventional Eulerian formulation. The weakness of the Eulerian scheme mainly lies in its inability to identify the 'bad seed' that ultimately leads the uprising. In the traditional marching algorithms of the Eulerian formulation, the resolution also appear to suffer in the presence of extensive reversed flow, which is typically prerequisite to unsteady separation. We have developed during the past year a time-accurate 2D boundary-layer Euler program, by formulating the unsteady boundary layer as an initial-value problem with spatial boundary conditions. It proves to be able to resolve the typical 'spike' signature of the displacement thickness at the inception of separation, which seems to be now generally accepted since the Lagrangian calculations of van Dommelen and Shen (1980). A comparison of the newly developed Eulerian vs. the earlier Lagrangian results for the bench-mark case of the impulsively-started cylinder is shown in Fig. 1. The absolute values of the spike differ because of the limited resolution of both methods at the mathematical singularity. It is the unmistakable occurrence of the spike that identifies separation.

With both the Lagrangian and the Eulerian programs as working tools, serious research on the possible control of unsteady boundary-layer separation and its optimization could actually begin. In principle we should continuously watch for the emergence and development of 'bad seeds' with the Lagrangian, and test the efficacy of various means of control to suppress the bad behavior. Other seeds turning into bad ones can also be tagged and dealt with. The 'lead time' for intervention is an equally intriguing aspect of the dynamics of separation. (It cries for a theoretical analysis, but we have yet to be able to formulate.) The Eulerian serves both as an alternate to the Lagrangian to circumvent the distortion problem, and as a possibly easier implementation of the control details. The technical aspects of switching from one code to the other are not expected to be a bottleneck but remains to be done.

Initial experimentation of control by surface suction for the impulsively-started cylinder have been reported by Shen (1990). The results substantiate the common-sense expectation that sufficient suction must be able to remove all 'bad seeds', hence separation — like massive mastectomy, while less suction is needed with earlier intervention, an indication of the role of the 'lead time'. Presented here are some additional results of applying suction to the impulsively started circular cylinder, which normally separates at (dimensionless) time $t = 1.5$:

Case (1) -- Fairly massive suction over the rear half, with peak at the rear stagnation point, starting from $t = 1.3$, as shown in sketch of Fig. 2(a). The suction is applied too late and does not capture the bad seed, as Fig. 2(b) shows substantial reduction of boundary layer thickness in the rear but the spike still appears at $t = 1.5$ and $X = 110^\circ$, same as without suction.

Case (2) -- Less total suction but concentrated more around $X = 110^\circ$, starting still from $t = 1.3$, Fig. 3(a). The spike appearance is delayed to $t = 1.55$ and $X = 125^\circ$ in Fig. 3(b), suggesting that the separation is now from a new group of bad seeds. There is some success with much reduced expenditure.

Case (3) -- Similar to case (2) but moving the suction region along the surface with a speed determined by a feedback from the boundary layer growth, reducing suction magnitude to a half, starting still from $t = 1.3$, Fig. 4(a). The spike now appears at $t = 1.7$ and $X = 127^\circ$ approximately. Thus more improvement is achieved with less effort.

The control strategy used in case (3) above is primitive, simply synchronizing the peak of the applied suction with the location of the maximum of the 'blowing velocity' $d(U\delta^*)/dx$, U being the free stream velocity at the wall and δ^* the displacement thickness. The suction strength Q is another parameter at our disposal. As a trial, we next regulate the peak suction not only to occur at the location of the calculated maximum blowing velocity but also to have exactly the same magnitude. Thus the applied suction is programmed as represented in Fig. 5 (a). The calculated displacement thicknesses, shown in Fig. 5 (b), are seen to be without the spike feature; the boundary layer remains attached for time up to $t = 2.5$.

These results are but crude examples of how to optimize the applied suction and achieve some control over the time and location of the inception of unsteady separation. In practical design, other precursors of the nascent spike, such as the flow reversal point on the wall, could replace the maximum 'blowing velocity' in actuating the control, and feedback loops may be added.

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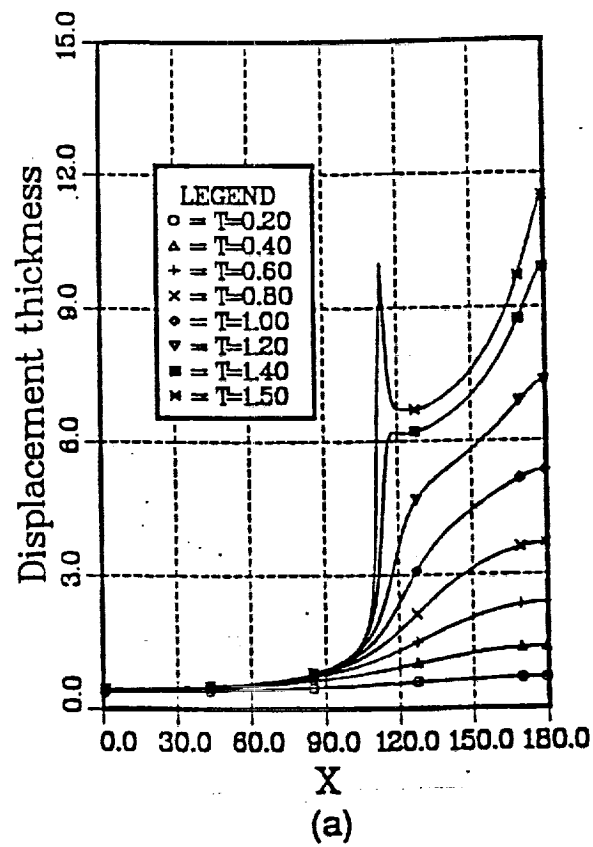
References:

Shen, S.F. and Wu, T. "Unsteady Separation over Maneuvering Bodies", AIAA Paper 88-3542, 1988.

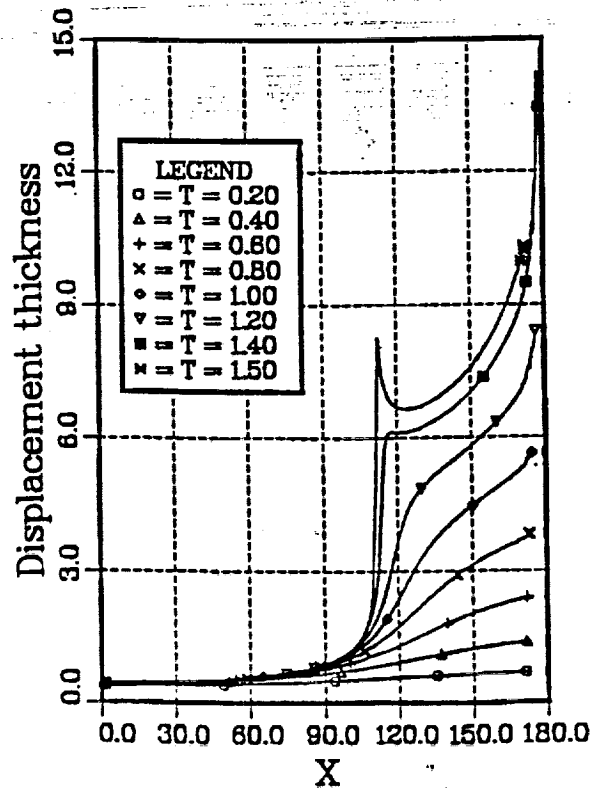
Shen, S.F. "Lagrangian View of Unsteady Separation", invited presentation at Workshop on Analytical Methods in Unsteady Separation, Columbus, OH, sponsored by U.S. Army Research Office, Jan. 25-26, 1990.

Van Dommelen, L.L. and Shen, S.F. "The Spontaneous Generation of the Singularity in a Separating Laminar Boundary Layer", J. Comp. Phy., vol. 38, 1980, pp. 125-140.

Wu, T. "Unsteady Incompressible Boundary-Layer Separation over a Two-Dimensional Impulsively Started Elliptic Cylinder by Lagrangian Method", MS Thesis, Cornell University, 1985.



(a)

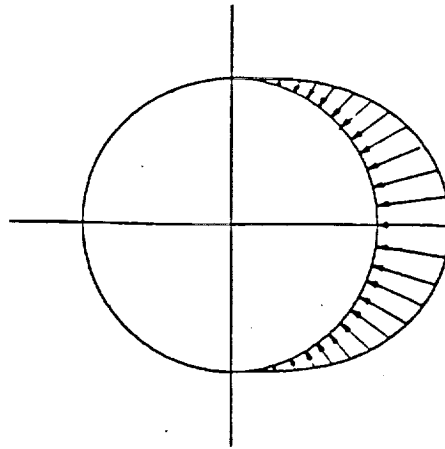


(b)

Fig. 1 Displacement Thickness on an Impulsively Started Circular Cylinder

(a) Eulerian

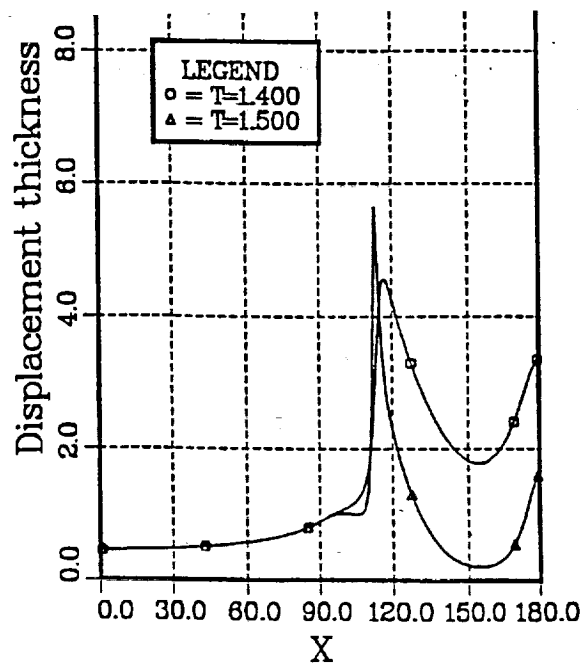
(b) Lagrangian



(a) Suction Distribution along the Circular Cylinder

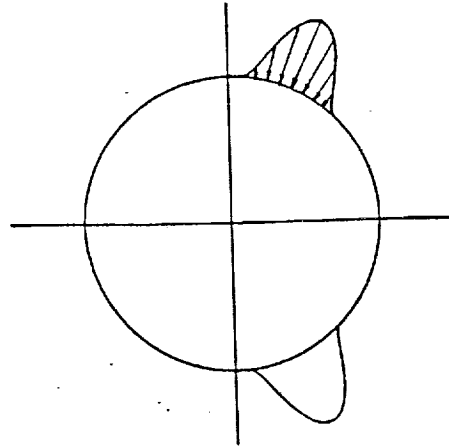
$$V_s = 0.5Q (1.0 - \cos((X-X_0)/(X_1-X_0)*2\pi))$$

$$Q = -50.0 \quad X_0 \leq X \leq X_1 \quad X_0 = 90.70^\circ \quad X_1 = 269.30^\circ$$

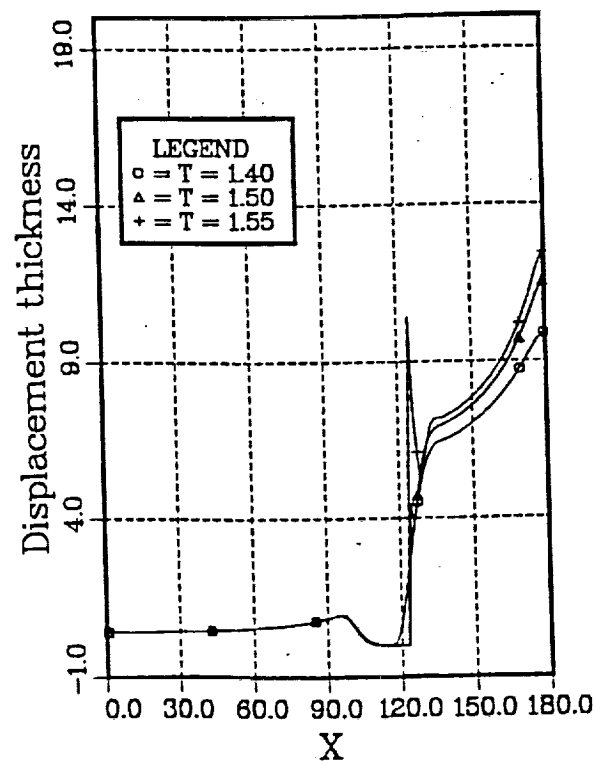


(b) Calculated Displacement Thicknesses at $t = 1.4$ and 1.5 .

Fig. 2 Displacement Thicknesses on an Impulsively Started Circular Cylinder with Suction Imposed when $t = 1.30$, Case (1).

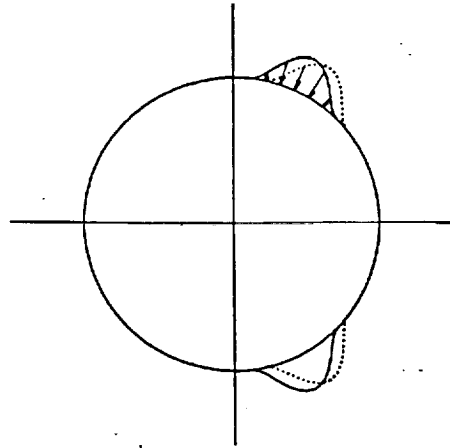


- (a) Suction Distribution along the Circular Cylinder
 $V_s = 0.5Q (1.0 - \cos((X-X_0)/(X_1-X_0)*2\pi))$
 $Q = -50.0 \quad X_0 \leq X \leq X_1 \quad X_1 - X_0 = 39.38^\circ$



- (b) Calculated Displacement Thicknesses at $t = 1.4$ and 1.55 .

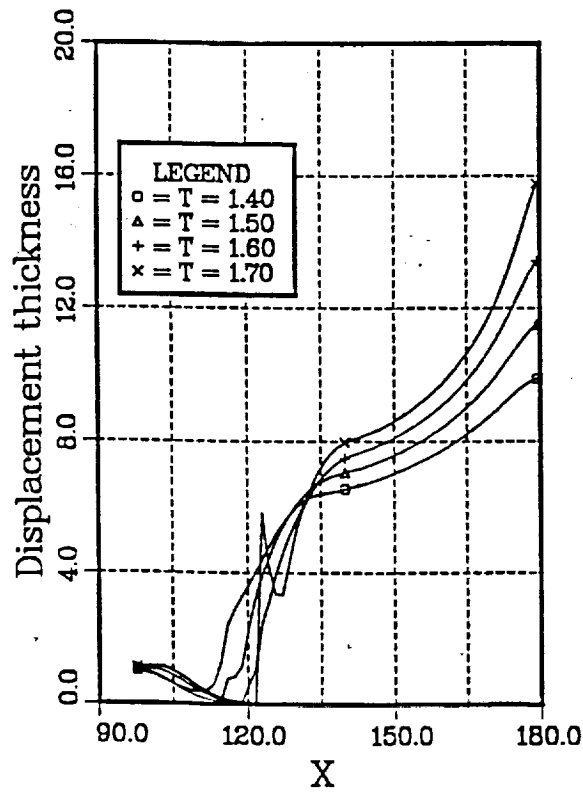
Fig. 3 Displacement Thicknesses on an Impulsively Started Circular Cylinder with Suction Imposed when $t = 1.30$, Case (2).



(a) Moving Suction Distribution along the Circular Cylinder

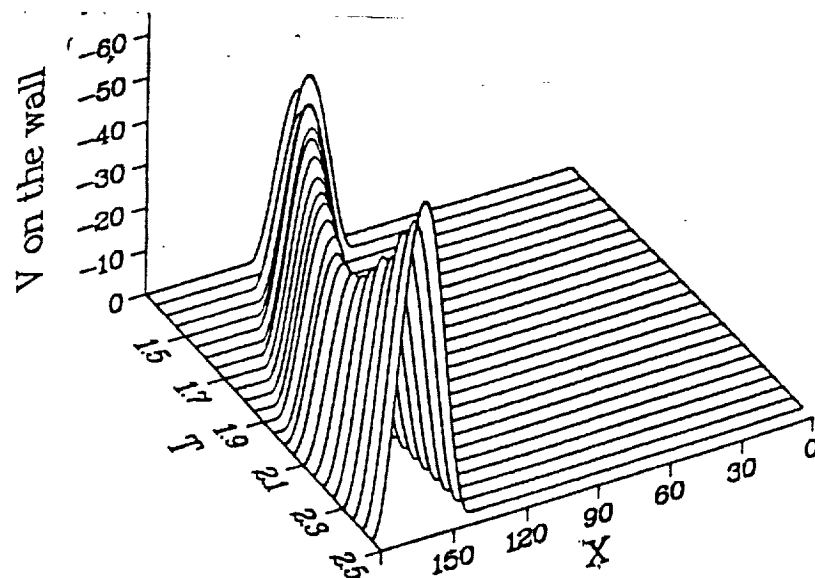
$$V_s = 0.5Q (1.0 - \cos((X - X_0)/(X_1 - X_0) * 2\pi))$$

$$Q = -25.0 \quad X_0 \leq X \leq X_1 \quad X_1 = X_0 + 39.38^\circ$$

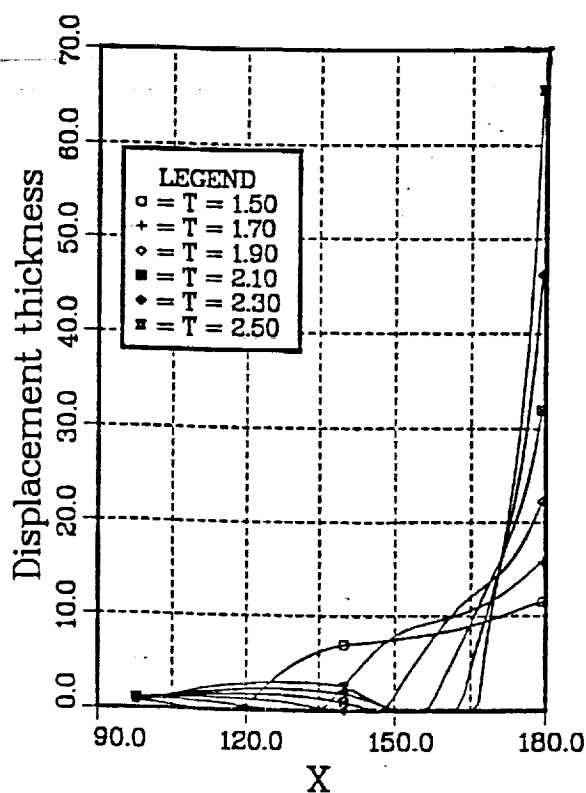


(b) Calculated Displacement Thicknesses at $t = 1.4, 1.5, 1.6$ and 1.7 .

Fig. 4 Displacement Thicknesses on an Impulsively Started Circular Cylinder with Suction Imposed when $t = 1.30$, Case (3).



(a) Programmed Suction Distribution at Different Times
 $V_s = 0.5Q (1.0 - \cos((X-X_0)/(X_1-X_0)*2\pi))$
 $Q = \text{Max Blowing Velocity } X_0 \leq X \leq X_1 \quad X_1-X_0 = 39.38^\circ$



(b) Calculated Displacement Thicknesses at $t = 1.5$ and later.

Fig. 5 Displacement Thicknesses on an Impulsively Started Circular Cylinder with Programmed Suction, $t_s = 1.4$.